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Published in:
Monthly Notices of the Royal Astronomical Society

DOI:
[10.1046/j.1365-8711.2001.04928.x](https://doi.org/10.1046/j.1365-8711.2001.04928.x)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2001

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Caccianiga, A., Marcha, M. J. M., Thean, A., & Dennett-Thorpe, J. (2001). EVN observations of low-luminosity flat-spectrum active galactic nuclei. *Monthly Notices of the Royal Astronomical Society*, 328(3), 867-872. <https://doi.org/10.1046/j.1365-8711.2001.04928.x>

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EVN observations of low-luminosity flat-spectrum active galactic nuclei

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Accepted 2001 August 13. Received 2001 August 3; in original form 2001 April 12

ABSTRACT

We present and discuss the results of very-long baseline interferometry (VLBI, EVN) observations of three low-luminosity ($P_{5\text{GHz}} < 10^{25} \text{ W Hz}^{-1}$) broad emission line active galactic nuclei (AGNs) carefully selected from a sample of flat-spectrum radio sources (CLASS). Based on the total and the extended radio power at 5 and at 1.4 GHz respectively, these objects should be technically classified as radio-quiet AGN and thus the origin of their radio emission is not clearly understood. The VLBI observations presented in this paper have revealed compact radio cores which imply a lower limit on the brightness temperature of about $3 \times 10^8 \text{ K}$. This result rules out a thermal origin for the radio emission and strongly suggests an emission mechanism similar to that observed in more powerful radio-loud AGNs. Since, by definition, the three objects show a flat (or inverted) radio spectrum between 1.4 and 8.4 GHz, the observed radio emission could be relativistically beamed. Multi-epoch VLBI observations can confirm this possibility in two years' time.

Key words: galaxies: active – galaxies: Seyfert – radio continuum: galaxies.

1 INTRODUCTION

The origin of the bimodality in radio luminosities of the quasar population remains a puzzle in AGN studies. This is as a result of the fact that, apart from the strength of the radio emission, radio-quiet and radio-loud (RQ and RL, respectively) AGNs share many of the same properties across the electromagnetic spectrum. It has been proposed (Terlevich et al. 1992) that in the case of the RQ AGNs, the radio emitting mechanism could be due to starburst phenomena in a very dense environment, whereas in the case of RL AGN the radio emission is due to the presence of radio jets. However, the detection of strong and compact (at VLBI resolution) nuclei in many RQ AGNs (Blundell & Beasley 1998) suggests that, at least in some RQ AGN, a non-thermal jet-like engine is at work.

With the increasing sensitivity of radio surveys, it has been shown that some local RQ AGNs (Seyfert galaxies) actually possess weaker versions of the jets seen in their radio-loud counterparts (e.g. Mazzarella et al. 1991; Pedlar et al. 1993; Kukula et al. 1993, 1996; Falcke, Wilson & Simpson 1998; Capetti et al. 1999; Thean et al. 2000). The study of the properties of these weak jets is clearly of fundamental importance to understand why in some objects the formation and/or the evolution of large-scale jets is inhibited. In particular, it would be interesting to know if the weak radio jets found in RQ objects are relativistic, like those found in RL AGNs. If so, when the source is seen along the jet, we expect to see some relativistic effects, like superluminal (SL)

motion or high brightness temperature ($> 10^{11} \text{ K}$) radio components, similar to those observed in BL Lac objects.

Falcke, Sherwood & Patnaik (1996) have identified a number of AGNs, selected from the Palomar–Green catalogue (PG) whose radio luminosity, if compared with the optical one, is intermediate between the typical RQ and RL AGNs. The distinction between RQ and RL object is commonly based on the radio-to-optical flux ratio (R) defined as (Kellerman et al. 1994)

$$R = \frac{S_{5\text{GHz}}}{S_{4400\text{\AA}}}$$

where $S_{5\text{GHz}}$ and $S_{4400\text{\AA}}$ are respectively the radio (at 5 GHz) and optical (at 4400 Å) flux densities. RQ and RL AGNs are respectively defined (Kellerman et al. 1994) with R below and above 10, while flat radio spectrum AGNs with $10 < R < 250$ are classified by Falcke et al. (1996) as radio intermediate (RI) AGNs. Falcke et al. (1996) present evidence that RI AGNs are RQ AGNs whose weak radio jet is pointing toward the observer and, as a consequence, the radio emission is beamed in that direction. In one of the objects selected by Falcke et al. (1996), namely the Seyfert galaxy III Zw 2, evidence for a superluminal jet has been presented (Brunthaler et al. 2000).

The confirmation that RQ AGNs have relativistic jets would be of great interest for our understanding of the radio-loud/radio-quiet dichotomy. More than finding a few examples of relativistic jets in RQ AGNs it would be important to quantify the percentage of RQ AGNs that present this characteristic. To this end, a systematic

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search for relativistic effects in a well defined and complete sample of RQ/RI AGNs would be very useful.

In this paper we present VLBI observations with the European VLBI Network (EVN) of three low-redshift ($z < 0.1$) RQ/RI AGNs carefully selected from a deep survey of flat spectrum radio sources. The goal of this small pilot sample is to test the efficiency with which radio criteria may be used to find beamed RQ AGNs.

Throughout this paper we use $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0$.

2 SELECTION STRATEGY

In the case of radio-loud AGNs the ‘classical’ starting point to look for beamed objects (called ‘blazars’) is a radio survey of flat-spectrum sources, since a flat or inverted spectrum in the radio band is the most easily recognized indication of relativistically beamed emission. Until recently the radio surveys used to select flat-spectrum AGN have had flux limits of around 1 Jy or higher (e.g. Kühr et al. 1981). Because the intrinsic power of a RQ AGN is, on average, two or three orders of magnitude lower than that of a RL AGN, these surveys would be unlikely to contain a useful fraction of beamed RQ objects.

For this reason, we decided to look for beamed RQ/RI objects using the deepest available sample of flat spectrum radio sources, namely the CLASS survey (Myers et al., in preparation). This survey is defined as follows:

- (i) $S_{5\text{GHz}} \geq 30 \text{ mJy}$;
- (ii) $\alpha_5^{1.4} \leq 0.5$ ($S \propto \nu^{-\alpha}$);
- (iii) $0^\circ < \delta < 75^\circ$.

Since a RQ/RI AGN is expected to have, on average, bright optical nuclear emission, we restrict the search to the radio sources in CLASS with a bright optical counterpart. A complete subsample of optically bright objects ($R < 17.5$) has been already selected from CLASS and presented in Marchã et al. (2001). About 70 per cent of the 325 objects contained in this sample have a spectroscopical classification (Caccianiga et al. 2001). Since this sample has been

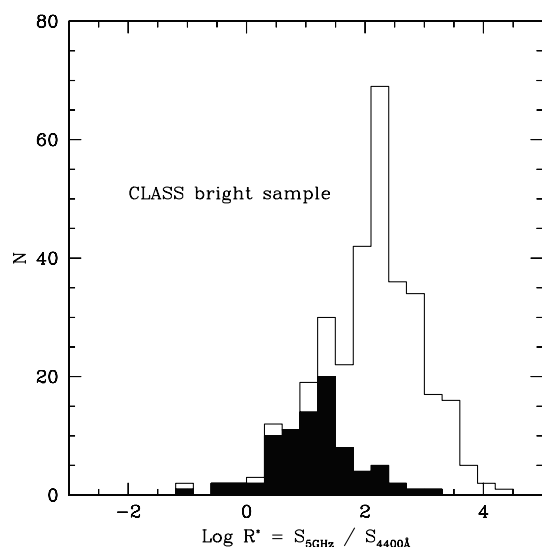


Figure 1. Radio-to-optical flux ratio (R^*) for the 325 objects in the CLASS bright sample computed with the observed optical magnitude (galaxy + nucleus). The shaded area includes only the low-redshift ($z < 0.1$) sources.

designed to find low-luminosity blazars we expect that beamed RQ AGNs, if they really exist, are to be found among these sources.

For the 325 objects we have computed a ‘total’ R^* parameter (see Fig. 1) defined on the basis of the observed power at 5 GHz and of the observed red magnitude (m_R). Since the m_R includes both the galaxy and the nuclear emission, the R^* parameter differs from the nuclear R . For a moderate contribution from the host galaxy the value of R^* tends to be equal to the nuclear R but, for a significant amount of starlight, the value of R^* can be considerably lower than R .

Thus, the objects in Fig. 1 with R^* below 250 may well contain objects that would be classified as RL if optical AGN contribution alone were used to calculate R . At present, the computation of the nuclear R parameter for the sources in our sample is not possible since it requires additional high-resolution data (e.g. observations with the *Hubble Space Telescope*) to estimate the optical nuclear contribution. However, since the value of R^* is an upper limit on R , we can confidently say that all the RQ/RI objects present in the CLASS survey must be found among the objects with $R^* \leq 250$, although they are probably mixed up with some RL AGNs.

In order to exclude from the sample the RL AGNs we have used an additional selection criterion based on the radio power. Since the radio power at 5 GHz is expected to be affected by beaming, we have decided to use the extended radio power at 1.4 GHz. About 40 per cent of the sources fall in the region of sky covered by the FIRST survey (Becker, White & Helfand 1995) which is made with VLA in B-configuration. The relatively small beam size (FWHM of 5 arcsec which corresponds to linear sizes below 10 kpc, for $z < 0.1$) gives the possibility of measuring the extended radio flux at 1.4 GHz as follows:

$$S^{\text{ext}} = S^{\text{int}} - S^{\text{pk}},$$

where S^{int} and S^{pk} are the integrated and the peak fluxes given in the FIRST catalogue.

Thus, among the sources contained in the CLASS bright sample and falling in the region of sky covered by FIRST, we have selected our best candidates with the following additional criteria:

- (i) low-redshift objects ($z \leq 0.1$);
- (ii) Extended radio power at 1.4 GHz $< 5 \times 10^{22} \text{ W Hz}^{-1}$.

The reason why we have selected low- z objects is that they allow a more detailed analysis and, for instance, any superluminal motion can be detected after a few years.

In total, 22 objects fulfil these selection criteria. We consider this list of 22 objects the *sample of beamed RQ AGN candidates*. All these objects have $R^* < 250$ and all but one have $R^* < 100$. Moreover, the observed radio power at 5 GHz for all these objects is below $10^{25} \text{ W Hz}^{-1}$ which is the value often used to distinguish between RL and RQ AGNs (Kellermann et al. 1994). If the observed power is relativistically beamed, the intrinsic power is expected to be even lower than the measured value.

3 TARGET SELECTION FOR THE EVN OBSERVATIONS

The aim of this work is to study the properties of the selected objects looking for evidence of relativistic effects. The first step is a radio observation at VLBI resolution, in order to confirm (or rule out) a non-thermal origin for the observed radio emission. In general, a simple detection of the majority of the flux observed in the VLA map at VLBI resolution (beamsize of few milliarcsec)

Table 1. Objects selected for the EVN observation.

Name	Position (J2000)	$S_{1.4\text{ GHz}}$ (mJy)	$S_{5\text{ GHz}}$ (mJy)	$S_{8.4\text{ GHz}}$ (mJy)	z	$\log P_{5\text{ GHz}}$ (W Hz ⁻¹)	$\log P_{1.4\text{ GHz}}^{\text{ext}}$ (W Hz ⁻¹)	R^*
GBJ141343+433959	14 13 43.717 +43 39 45.01	48	39	27	0.089	24.13	22.56	50
GBJ151838+404532	15 18 38.903 +40 45 00.21	44	44	27	0.065	23.90	22.35	31
GBJ171914+485839	17 19 14.491 +48 58 49.44	145	164	206	0.024	23.61	22.51	31

Table 2. Results from EVN observations.

Name	Peak flux density (mJy beam ⁻¹)	Total flux density (mJy)	Beam size (mas)	rms (mJy beam ⁻¹)	PA (Deg)	T_B (K)
GBJ141343+433959	32.0	33.4	6.7×4.8	0.29	+82.2	$> 2.9 \times 10^8$
GBJ151838+404532	24.7	27.6	6.1×4.0	0.24	-72.4	$> 2.9 \times 10^8$
GBJ171914+485839 (A)	54.9	55.6	6.2×4.0	0.23	-80.4	$> 6.4 \times 10^8$
GBJ171914+485839 (B)	2.9	4.6	6.2×4.0	0.23	-80.4	$\sim 4 \times 10^6$

would imply a high brightness temperature ruling out the hypothesis of a thermal emission. The second step is the collection of more epochs of VLBI observation in order to look for superluminal motions.

As a pilot study, we have selected three objects from the 22 candidates, and observed these with the EVN. Since, according to the Unified Schemes (e.g. Wills 1999), a beamed source is supposed to be oriented in such a way that we can see the broad line region, we expect that a good candidate for beaming would have broad emission lines in the optical spectrum. Therefore, among the 22 objects in the sample, we have selected three sources that show broad emission lines.

The list of the observed targets is presented in Table 1 along with the radio position measured with the VLA (A-array) at 8.4 GHz (column 2), NVSS flux density at 1.4 GHz (column 3), GB6 flux density at 5 GHz (Column 4), VLA flux density at 8.4 GHz (column 5), redshift (column 6), radio power at 5 GHz (column 7), extended radio power at 1.4 GHz as measured from FIRST images (column 8), R^* parameter (column 9).

We discuss in detail the properties of the selected objects.

3.1 Properties of the selected sources

GBJ141343+433959 This object is classified from the literature as broad line radio galaxy (BLRG). It is the cD galaxy of the Abell 1885 cluster. The optical spectrum published in Crawford et al. (1995) and in Laurent-Muehleisen et al. (1998) shows relatively strong emission lines ([O II], H β , [O I], H α + [N II] and [S II]). GBJ141343+433959 is also a bright X-ray source detected in the Bright ROSAT All-Sky Survey (RASS, Voges et al. 1999). Its unabsorbed X-ray flux is 4.9×10^{-12} erg s⁻¹ cm⁻² in the 0.2–2.4 keV energy band corresponding to an X-ray luminosity of 1.7×10^{44} erg s⁻¹. This high X-ray luminosity is probably produced by the hot intercluster plasma. The object belongs also to the REX catalogue (Radio Emitting X-ray sources, Caccianiga et al. 1999).

GBJ151838+404532 This object is classified from the literature as type 1 Seyfert galaxy. Its optical spectrum (Laurent-Muehleisen et al. 1998) shows emission lines (H β , [O III], H α). As with the previous source, GBJ151838+404532 was also detected in the Bright RASS catalogue with an unabsorbed flux of 8.4×10^{-12} erg s⁻¹ cm⁻² and an X-ray luminosity of 1.6×10^{43} erg s⁻¹.

GBJ171914+485839 This object belongs to an interacting system (Arp 102A and Arp 102B) where Arp 102B is the object that shows AGN activity. The optical spectrum (e.g. Stauffer, Schild & Keel 1983) shows double-peaked broad emission lines (H β and H α) superimposed on narrow components. It is an X-ray source detected in the bright RASS catalogue with an unabsorbed flux of 9.2×10^{-12} erg s⁻¹ cm⁻² and an X-ray luminosity of 2.3×10^{42} erg s⁻¹.

In the radio band, GBJ171914+485839 has been detected as a compact source at VLBI resolution (at 5 GHz) by Biermann et al. (1981) with a total flux of 96 mJy and an upper limit on the size of 0.4 pc. At 4.9 GHz there is also a VLA observation in A-configuration (Puschell et al. 1986) that shows a total flux of 90 mJy mainly concentrated in an unresolved core. About 30 per cent of this flux, however, is distributed in a faint jet-like structure. Based on other single-dish observations, Puschell et al. (1986) conclude that any extended emission, if present, has to be much weaker than the typical extended emission in ‘normal’ radio galaxies.

4 EVN OBSERVATIONS

The three objects have been observed at 5 GHz with the European VLBI Network (EVN) on the 2000 June 4 in VLBA recording mode. Seven antennas were used for these observations (Effelsberg, Westerbork, Jodrell Bank, Medicina, Noto, Onsala, Torun). The total exposure time for each object was about 2 h. The data have been reduced at JIVE using the NRAO AIPS package.

The resulting maps are presented in Fig. 2 while in Table 2 we report, respectively: the name of the source (column 1), the peak flux density (column 2), the total flux density (column 3), the beam size (column 4), the rms (column 5), the position angle (column 6), the computed brightness temperature (or lower limit, column 7).

The noise for the three maps ranges from 0.23 to 0.29 mJy beam⁻¹ which is relatively low and close to the theoretical value. The three objects appear compact without any evidence of extended structure. Only in one case (GBJ171914+485839) a second component is detected at a distance of 21.9 milliarcsec away from the main component. The corresponding linear projected distance at the redshift of the source is about 15 pc. In 1981 this galaxy was observed with VLBI at 5 GHz, including Effelsberg, Westerbork and Green

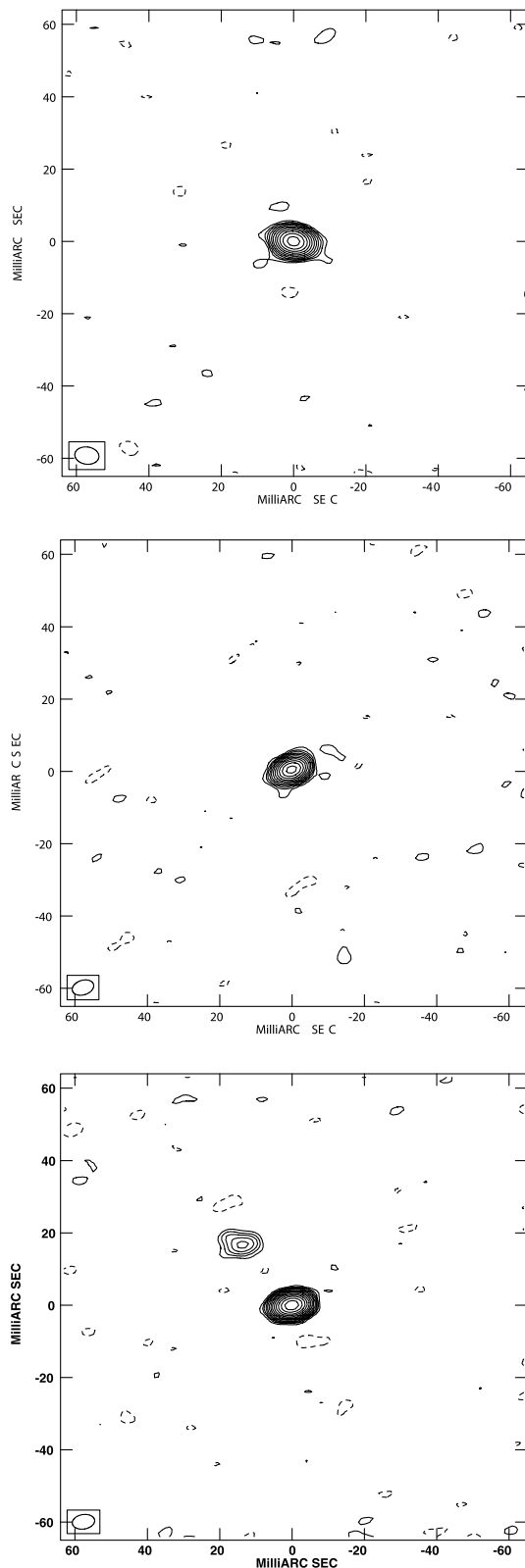


Figure 2. EVN maps at 5 GHz of the CLASS RQ/RI AGNs. The contour levels are: $-2.5, 2.5, 4, 5, 5.6, 8, 11.3, 16, 23, 32, 45, 64, 90, 128, 181$ and they are counted in units of rms value (see Table 2).

Bank (USA) antennas (Biermann et al. 1981). The object appeared unresolved in these observations and the second component was not seen. However, even though the resolution of the 1981 VLBI observation was good enough to separate the two

components, the rms was probably too large ($\sim 9\text{--}14$ mJy) to clearly detect the faintest peak.

Assuming an apparent superluminal velocity for this component, a second epoch observation taken two years after our observations should show an increment in the relative distance between the two components of more than 0.8 milliarcsec. This increment should be clearly detectable with observations at the same resolution (beam size of $\sim 4\text{--}7$ milliarcsec).

4.1 Brightness temperature limits

The simple fact that the three sources are detected and unresolved at the EVN resolution implies quite a high lower limit on the brightness temperature. At the frequency of 5 GHz the brightness temperature is given by

$$T_B = 7.2 \times 10^7 \frac{S_{5\text{GHz}}}{\Theta^2} \text{ K} \quad (1)$$

where $S_{5\text{GHz}}$ and Θ represent the observed flux density (in mJy) and the source size (in milliarcsec) respectively. Since all the detected components are unresolved (except for the second weak component in GBJ171914+485839) their size is expected to be lower than the beam size. A reasonable upper limit to the source size is half of the beamsize. By using this upper limit and the observed peak flux density we derive a lower limit for T_B (see Table 2). In general, for the three strongest components in the three objects the lower limit on T_B is larger than 10^8 K.

High values of brightness temperature are usually interpreted as strong indication for a non-thermal origin for the observed radio emission. Recently Smith, Lonsdale & Lonsdale (1998a) investigated the possibility that high- T_B and compact nuclei observed in a sample of luminous infrared galaxies (LIG) are produced by luminous radio supernovae generated by intense starburst activity. They found that in some cases the model can explain what is observed at VLBI resolution although the supernovae luminosity has to be extremely high and, in some cases, more than an order of magnitude higher than the supernovae discovered so far. It must be noted, however, that the lower limits on T_B derived for the objects studied by Smith et al. (1998a) are at least one order of magnitude below the ones inferred for the three sources presented in this paper. Moreover, the well-studied Arp 220, which is considered the prototype luminous infrared galaxy, when observed at VLBI (with a resolution similar to that achieved in our observations) shows a nucleus which is resolved into multiple components (Smith et al. 1998b) something that is not observed in the three sources presented here. Finally, there is also a difference in radio power between the LIGs and the three sources presented here: the VLBI radio power (at 1.6 GHz) measured for the LIGs in the Smith, Lonsdale & Lonsdale sample is below $10^{23} \text{ W Hz}^{-1}$ (except for MKN 231) while the radio power of the three CLASS sources measured at 5 GHz is above $10^{23} \text{ W Hz}^{-1}$.

We thus consider it unlikely that a model based on luminous radio supernovae can explain the high T_B observed in the three sources presented in this paper and we favour the hypothesis that we are observing a non-thermal emission from the AGN nucleus.

4.2 Variability

By comparing the total flux densities at 5 GHz in Table 1 and Table 2 we see that in GBJ151838+404532 and in GBJ171914+485839 the total fluxes measured with EVN are significantly below the fluxes in the GB6 catalog. This could be an

Table 3. Measurements of flux density at 5 GHz for GBJ171914+485839 at different epochs.

Date	Telescope	5 GHz (mJy)	Ref.
1981	VLBI	96	Biermann et al. (1981)
1981/03/10	VLA (A config.)	90	Puschell et al. (1986)
1994/05/07	VLA (B config.)	139	Laurent-Muehleisen et al. (1997)
2000/05/04	EVN	^a 60	This paper

^aThis is the sum of the flux densities of the two components (A and B).

indication either of variability or that some flux is missed in the EVN observations. However, in the case of GBJ151838+404532, a second (unrelated) source about 2 arcmin northward is probably contributing to the GB6 flux, since the large beamsize of GB (~ 3.5 arcmin) cannot resolve the two sources. Furthermore, Laurent-Muehleisen et al. (1997) give a flux density of 29 mJy at 5 GHz for this source measured with the VLA (A-configuration). This value is in good agreement with the one measured in the EVN observation (27.6 mJy).

In the case of GBJ171914+485839, clear evidence of variability is given by the different measurements at 5 GHz taken at different epochs (see Table 3), in particular by comparing the VLBI observations of Biermann et al. (1981) to ours. The observed variability is consistent with the hypothesis that this source is relativistically beamed.

5 RADIO-QUIET OR WEAK RADIO-LOUD AGNS?

As previously discussed, the 3 sources presented in this paper were classified as RQ AGN on the basis of the observed extended radio power at 1.4 GHz. However, the distinction between RL and RQ AGN based on the radio-power is not universally accepted. In a recent paper Ho & Peng (2001) suggested that a large fraction of the Seyfert galaxies, usually considered as the local counterparts of the RQ QSOs, are actually RL objects according to the Kellerman definition (nuclear $R > 10$) if the proper contribution from the nucleus is considered. If confirmed, this result would imply that the RL class of AGN extends to orders of magnitude below the usual dividing power of $10^{25} \text{ W Hz}^{-1}$ and has a large overlap with the range of radio power shown by ‘real’ RQ AGNs (i.e. objects with a nuclear R below 10).

In this case, the objects selected in the CLASS survey could be RL or RQ objects depending on the actual value of the nuclear R parameter. As already discussed, the computed R^* is just an upper limit and cannot be used to distinguish between RQ and RL objects.

Ho & Peng (2001) also found two independent correlations between the nuclear radio power ($P_{5 \text{ GHz}}$) and line luminosity ($L(\text{H}\beta)$) for RQ and RL objects. In principle, the location of an object in the $P_{5 \text{ GHz}}/L(\text{H}\beta)$ plane could be used to distinguish between RL and RQ objects. The line luminosities ($\text{H}\beta$) and the radio powers at 5 GHz of the three objects presented here are $\sim 10^{40} - 10^{41} \text{ erg s}^{-1}$ and $\sim 10^{23} - 10^{24} \text{ W Hz}^{-1}$ respectively. The position of these sources in the $P_{5 \text{ GHz}}/L(\text{H}\beta)$ plot is above the two best fits obtained by Ho & Peng (2001) for RL and RQ AGN respectively. This is expected if the observed radio power is relativistically beamed. Depending on the value of the beaming parameter, the three objects can move down in the $P_{5 \text{ GHz}}/L(\text{H}\beta)$ plane to the RL correlation line, if a beaming factor of 10–100 is

considered, or to the RQ correlation line, by considering a beaming factor of 100–1000. In the case of BL Lac objects, which are typical beamed RL AGN, the amplification factor is estimated to be around 100 (e.g. Urry & Padovani 1995) but with a large spread around this value depending on the plasma bulk velocity (Γ), the viewing angle (θ) and the fraction of luminosity emitted along the jet (f). Thus, both the RL and the RQ classifications are possible although the hypothesis that the three objects presented here belong to the faint tail of the RL population is probably the most reasonable since it does not require large amplification factors.

An estimate of the beaming factor, derived from future detections of SL motions in the selected objects, could be used to find the intrinsic radio power and, thus, determine the location of the objects in the $P_{5 \text{ GHz}}/L(\text{H}\beta)$ diagram. This can give an indication of whether the objects belong to the RQ class of AGN or to the faint tail of the RL objects.

6 SUMMARY AND CONCLUSION

Starting from a radio survey of flat-spectrum radio sources we have selected three objects that show weak extended radio components whose powers are in the range of a typical RQ AGN ($< 5 \times 10^{22} \text{ W Hz}^{-1}$). In addition, these objects are at low redshift and their optical spectra show broad emission lines. According to some authors (e.g. Terlevich et al. 1992) the radio emission could be produced by thermal mechanisms, like a high star formation rate in a dense environment. The EVN observations presented here, however, show in each target a bright and unresolved radio core whose brightness temperature ($> 10^8 \text{ K}$) is too high to be as a result of starburst emission. Hence, non-thermal emission (maybe owing to the presence of a jet-like structure like in more powerful RL AGN), is probably causing the observed radio emission.

The main reason we undertook this study was to investigate the hypothesis that low-power AGNs, usually classified as RQ, can produce relativistic jets. To this end we have focused our attention on the population of sources for which direct evidence of relativistic outflows ought to be obtained most easily, namely the low-luminosity flat-spectrum AGN. These objects could be RQ AGN whose relativistic jets are viewed close to end-on. Studying the proper motions of radio components in a large enough sample of such sources should uncover apparent superluminal motions if RQ AGN produce relativistic jets.

Our initial results are promising: all three sources we observed contain high-brightness temperature cores which can be monitored. One object (GBJ171914+485839) is particularly interesting because it is resolved into two components: superluminal motion in this source would be apparent within two years.

The discovery that some low-power AGNs have relativistic jets would either imply that RQ AGNs are intrinsically similar to RL objects or it may support the hypothesis, recently presented by Ho

& Peng (2001), that the RL class of AGN extends down to very low radio powers and it overlaps significantly with the RQ AGN class. Both hypothesis have interesting implications for the RL/RQ dichotomy debate.

ACKNOWLEDGMENTS

We thank the staff at the JIVE institute, and in particular Denise Gabuzda, for their friendly support during all the phases of EVN observation (proposal preparation, scheduling and data analysis). We acknowledge support from the European Commission under the IHP Programme (ARI) contract No. HPRI-CT-1999-00045. This research was supported in part by the European Commission Training and Mobility of Researchers (TMR) program, research network contract ERBFMRX-CT96-0034 ‘CERES’.

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